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The Flatness and Sudden Evolution of the Intergalactic Ionizing Background

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ABSTRACT

The ionizing background of cosmic hydrogen is an important probe of the sources and absorbers of ionizing radiation, their evolution and relationship, in the post-reionization universe. Previous studies show that the ionization rate should be very sensitive to changes in the source population: as the emissivity rises, absorbers shrink in size, increasing the ionizing mean free path and, hence, the ionizing background. By contrast, observations of the ionizing background find a very flat evolution from $z \sim 2 - 5$, before falling precipitously at $z \sim 6$. We resolve this discrepancy by pointing out that, at $z \sim 2 - 5$, optically thick absorbers are associated with the same collapsed halos that additionally host ionizing galactic sources. Thus, an increasing abundance of galaxies is compensated for by a corresponding increase in the absorber population, which moderates the instability in the ionizing background. However, by $z \sim 5 - 6$, gas outside of halos dominates the absorption, the coupling between sources and absorbers is lost, and the ionizing background evolves rapidly. Our halo based model reproduces observations of the ionizing background, its flatness and sudden decline, as well as the redshift evolution of the ionizing mean free path. Our work suggests that, through much of their history, both star formation and photoelectric opacity in the universe track halo growth.

Key words: dark ages, reionization, first stars—intergalactic medium—galaxies: evolution—galaxies: high-redshift—quasars: absorption lines—cosmology: theory

1 INTRODUCTION

The ionizing background in the intergalactic medium (IGM) depends on both the production and absorption rate of photons beyond the Lyman limit. Because stars dominate this production, the ionizing background is an important probe of the buildup of the star formation rate density and evolution in the ionizing escape fraction. This is particularly true at high-redshift, where a significant population of galaxies lie below the current UV detection limits and escaping Lyman-limit photons are completely absorbed by intervening gas. McQuinn et al. (2011) emphasized the extreme sensitiv-

ity of the background ionization rate, Γ , to the source ionizing emissivity, ϵ , and found $\Gamma \propto \epsilon^{2-4.5}$, with the exponent increasing toward higher redshifts.

However, these authors also pointed out that this sensitive dependence implies a puzzling inconsistency between recent observations demonstrating the nearly flat evolution of the ionizing background from $z \sim 2-5$ (Bolton et al. 2005; Becker et al. 2007; Faucher-Giguère et al. 2008; Becker & Bolton 2013) and a rapidly evolving star formation rate density in the universe over the same redshift interval (e.g., Bouwens et al. 2012). Only at $z > 5$ does the background ionization rate appear to evolve rapidly (Fan et al. 2006; Bolton & Haehnelt 2007; Wyithe & Bolton 2011; Calverley et al. 2011).

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Of course, the ionizing escape fraction, f_{esc} , of galaxies, which modulates the star formation rate density to produce the ionizing emissivity, is highly uncertain at high redshift (e.g., Ferrara & Loeb 2013). Thus, recent work has focused on fine tuning the evolution of f_{esc} to produce consistency between observations of (1) the column density distribution of absorbers, (2) the star formation rate density, and (3) the background ionization rate (e.g., Haardt & Madau 2012; Kuhlen & Faucher-Giguère 2012).

We suggest that a more generic solution to this puzzle may lie in recent suggestions, both theoretical and observational, that, in addition to the production rate of ionizing photons, galaxies are also connected to Lyman-limit systems (LLSs), which dominate the absorption of such photons (e.g. Rauch et al. 2008; Steidel et al. 2010; Rudie et al. 2012; Font-Ribera et al. 2012; Rauch & Haehnelt 2011; McQuinn et al. 2011; Rahmati & Schaye 2014; Faucher-Giguere et al. 2014). Thus, an increasing ionizing emissivity associated with a growing abundance of galaxies could be balanced by a corresponding increase in the population of absorbers. If true, quasar absorption lines in general, and the ionizing background in particular, could be useful probes, not only of the star formation in galaxies, but also of the gas in and around them.

In this paper, we test the hypothesis that a link between LLSs and galaxies can explain the flat evolution of $\Gamma(z)$ observed by Becker & Bolton (2013). We develop simple, semi-analytic prescriptions to describe the distribution and ionization state of gas in dark matter halos as well as the galaxies hosted in the same structures. We then compute the resulting background ionization rate and its evolution. Moreover, we show that our simple model breaks down at $z \sim 5$ when low-overdensity gas outside halos must contribute to absorption, which naturally decouples sources from absorbers and enables the observed precipitous drop in Γ .

In §2, we begin by developing analytic insight into the dependence of Γ on the ionizing emissivity. We then describe our semi-analytic models for absorbing gas and the production of ionizing photons associated with dark matter halos in §3. In §4, we present our results for the evolution of Γ , comparing them to recent observations, and discuss the sensitivity of these results to model assumptions in §5. Finally, we conclude in §6.

Throughout this work, we assume a Λ CDM cosmology with $(h, \Omega_m, \Omega_\Lambda, \Omega_b, \sigma_8) = (0.7, 0.28, 0.72, 0.046, 0.82)$.

2 ANALYTIC INSIGHT

To derive physical insight, we begin with analytic scaling arguments similar to those in McQuinn et al. (2011). In the Miralda-Escudé et al. (2000) model of the intergalactic medium, gas above a critical overdensity, Δ_i , is assumed to be completely neutral, while less dense material is completely ionized. This gas, with mean free

path λ , then filters the emission from sources, with ionizing emissivity ϵ , to produce the background ionization rate:

$$\Gamma \propto \epsilon \lambda. \quad (1)$$

Here, the mean free path is related to the properties of a population of identical absorbers by

$$\lambda \propto (n_a \sigma_a)^{-1}, \quad (2)$$

where n_a is the number density of absorbers and $\sigma_a \propto r_a^2$ is the absorber cross-section with r_a the typical inverse-Stromgren radius of an absorber setting the size of the optically thick core.

Let us approximate LLSs as spherically symmetric absorbers, each with density profile $n(r) \propto r^{-\alpha}$, illuminated by a meta-galactic ionizing background. Outside the core, we assume that the ionization rate equals the recombination rate in the optically thin limit,

$$\Gamma n_{\text{HI}} \propto n_{\text{H}}^2, \quad (3)$$

where n_{H} and n_{HI} are the number densities of the total and neutral gas, respectively. The size r_a is set by assuming a fixed value of the ionizing optical depth for the gas to become optically thick,

$$\tau = \int_{r_a}^{\infty} n_{\text{HI}} \sigma_{\text{HI}} dr \propto \frac{n_{\text{H}}^2(r_a) r_a}{\Gamma} \propto \text{constant}, \quad (4)$$

where σ_{HI} is the hydrogen ionization cross-section at 912 Å. Substituting for the density, we find

$$r_a \propto \Gamma^{1/(1-2\alpha)}, \quad (5)$$

which relates the core radius of an absorber to the intensity of the ionizing background. Combining with equations 1 and 2 yields

$$\frac{\epsilon}{n_a} \propto r_a^{3-2\alpha} \quad (6)$$

and

$$\Gamma \propto \left(\frac{\epsilon}{n_a}\right)^{(2\alpha-1)/(2\alpha-3)} \propto \left(\frac{\epsilon}{n_a}\right)^\theta, \quad (7)$$

where $\theta \equiv d \ln \Gamma / d \ln \epsilon = (2\alpha - 1)/(2\alpha - 3)$. If the density profile of absorbers is isothermal with $\alpha = 2$ and their abundance, n_a , is held fixed, then $\theta = 3$, and Γ will vary sensitively with ϵ . In essence, as the ionization rate increases in response to an increasing emissivity, the size of absorbers shrinks, leading to a smaller mean free path and an even larger ionization rate. This is the same basic result found by McQuinn et al. (2011), who derived similarly sensitive scalings ($\theta \approx 2-4.5$) using the density profiles in numerical simulations, effectively holding n_a constant while varying ϵ . Note that holding n_a constant is also equivalent to adopting the ansatz from Miralda-Escudé et al. (2000) that the typical distance between absorbers is proportional to the volume filling factor of neutral gas to the $-2/3$ power.

To gain further insight, let us describe the emissivity as the product of the number density of sources, n_s , the average ionizing luminosity produced per source,

L_s , and the ionizing escape fraction f_{esc} . While the specific star formation rate and resulting luminosity of galaxies evolves with the cosmic accretion rate and decreases with decreasing redshift (e.g., Davé et al. 2012; Muñoz 2012; Stark et al. 2013), the main driver for the increasing star formation rate density of the universe down to $z \sim 2$ is the growing number of sources (e.g., Trenti et al. 2010; Muñoz & Loeb 2011). Recent studies have effectively balanced this evolving n_s with an evolving f_{esc} (Haardt & Madau 2012; Kuhlen & Faucher-Giguère 2012). However, if f_{esc} is held fixed, then, although Γ is a sensitive function of $f_{\text{esc}} L_s n_s/n_a$, the key question is how independent are n_s and n_a . If the abundance of sources can grow without changing the absorber population, then we retain the McQuinn et al. (2011) result. However, if $n_s \propto n_a$ so that the formation of additional sources also adds proportionally more absorbers to the universe, then the background ionization rate will be relatively insensitive to the changing source emissivity.

That sources and absorbers are closely related is well-known from numerical simulations (e.g., Rahmati & Schaye 2014). The difficulty, however, lies in a self-consistent treatment of the source emissivity and the meta-galactic background over a volume large enough to span the ionizing mean free path while resolving the density distribution in halos around sources. In the following section, we explore the related evolution of absorbers and sources using a semi-analytic treatment.

3 SEMI-ANALYTIC TREATMENT

In this section, we present semi-analytic prescriptions for absorbers (§3.1) and sources (§3.2) to explore the connection between the two in more detail. In §3.3, we give a brief summary of the models with a list of free parameters.

3.1 Absorber Model

We assume that neutral gas associated with dark matter halos, rather than diffuse clouds in the IGM, dominates the column density distribution for LLSs (e.g., Rahmati & Schaye 2014). We take the gas profile to trace that of the dark matter in the halo.¹ For an NFW profile (Navarro et al. 1997), the distribution of overdensity, Δ , is

$$\Delta = \frac{c_{\text{vir}}^3 \Delta_{\text{vir}}}{3 A(c_{\text{vir}})} \left[\frac{1}{(r/r_a)(1+r/r_a)^2} \right], \quad (8)$$

where $A(c_{\text{vir}}) \equiv \ln(1+c_{\text{vir}}) - c_{\text{vir}}/(1+c_{\text{vir}})$, and we adopt the Dutton & Macciò (2014) fitting model for the concentration parameter $c_{\text{vir}} \equiv r_{\text{vir}}/r_a$ as a function of halo

¹ This assumption is unlikely to be correct in detail, but our results are robust to variations. See §5.2 on the sensitivity of our results to this profile choice.

mass and redshift. Further, r_{vir} is the halo virial radius enclosing the non-linear critical overdensity, Δ_{vir} , required for spherical collapse (e.g., Barkana & Loeb 2001). $\Delta_{\text{vir}} \approx 18\pi^2$ in the matter-dominated epoch but evolves at low-redshift when dark energy becomes important.

Given this distribution of over-density, the physical neutral gas density is $n_{\text{H}} = x_{\text{H}} n_{\text{H}}$, where $n_{\text{H}} = \Delta \rho_{\text{crit}} \Omega_b (1 - Y_{\text{He}})/m_p$, the helium fraction is $Y_{\text{He}} = 0.24$, the neutral gas fraction x_{H} is given by ionization equilibrium:

$$x_{\text{H}} \Gamma_{\text{local}} = \alpha_{\text{rec}} n_{\text{H}} (1 - x_{\text{H}})^2, \quad (9)$$

α_{rec} is the recombination coefficient, and Γ_{local} is the ionization rate in gas with hydrogen density n_{H} and subject to a background ionization rate Γ . We compute Γ_{local} using the prescription derived by Rahmati et al. (2013) from numerical simulations that include radiative transfer and the effects of self-shielding:

$$\frac{\Gamma_{\text{local}}}{\Gamma} = 0.98 \left[1 + \left(\frac{n_{\text{H}}}{n_{\text{ss}}} \right)^{1.64} \right]^{-2.28} + 0.02 \left[1 + \frac{n_{\text{H}}}{n_{\text{ss}}} \right]^{-0.84}, \quad (10)$$

where

$$n_{\text{ss}} \approx 6.73 \times 10^{-3} \text{ cm}^{-3} \left(\frac{T}{10^4 \text{ K}} \right)^{0.17} \left(\frac{\Gamma}{10^{-12} \text{ s}^{-1}} \right)^{2/3} \quad (11)$$

is the number density at which the gas begins to self-shield, and T is the temperature of the IGM. We set a constant temperature of $T = 10^4 \text{ K}$ throughout this work, but note that equation 11 depends only weakly on this choice. We further take α_{rec} to be the value for Case A recombinations, $\alpha_{\text{A}} \approx 4.2 \times 10^{-13} (T/10^4 \text{ K})^{-0.76}$, since equation 10 automatically includes the effect of recombination radiation (Rahmati et al. 2013). Finally, we emphasize that, though we adopted the most accurate prescriptions available to implement in our model, the details of these prescriptions are not critical to our results (see §5.2).

Our modeling of absorbers within halos is appropriate as far as the density profile holds but breaks down when gas lying outside of halos, which no longer traces the assumed profile, contributes significantly to the absorption of ionizing photons. We can estimate the redshift at which this occurs by asking when the overdensity at the virial radius of halos exceeds that associated with LLSs. We first compute this associated overdensity by assuming the Schaye (2001) description of identical absorbers with sizes given by the Jeans scale in the optically thin limit of ionization equilibrium (see also Furlanetto & Oh 2005):

$$\Delta_i \approx 45 \left(\frac{\Gamma}{10^{-12} \text{ s}^{-1}} \right)^{2/3} \left(\frac{1+z}{7} \right)^{-3} \times \left(\frac{N_{\text{LLS}}}{10^{17} \text{ cm}^{-2}} \right)^{2/3} \left(\frac{T}{10^4 \text{ K}} \right)^{0.17}, \quad (12)$$

where N_{LLS} is the neutral column density of a LLS. Note that, while these assumptions are unlikely to be

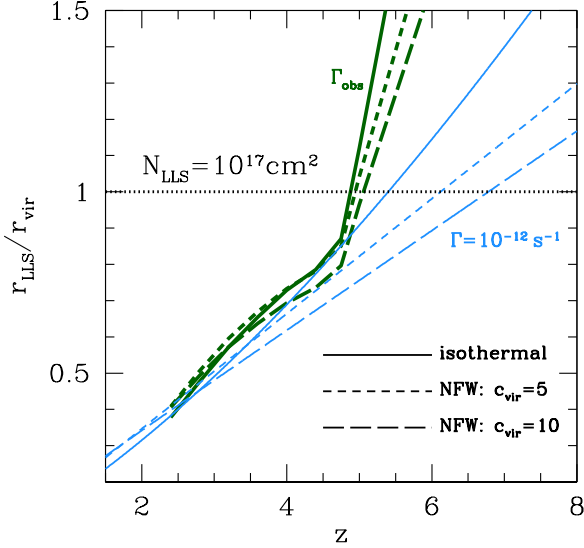


Figure 1. The radius, r_{LLS} , at which the local gas overdensity exceeds the critical value, Δ_i , corresponding to LLSs with $N_{\text{HI}} \sim 10^{17} \text{ cm}^2$ as a function of redshift. Thin (blue) lines assume a fixed value of $\Gamma = 10^{-12} \text{ s}^{-1}$, while thick (green) lines adopt the Becker & Bolton (2013) mean values at $z = 2.4\text{--}4.75$ and an average of measurements from Wyithe & Bolton (2011) and Calverley et al. (2011) at $z = 5$ and 6. We show results for an isothermal halo profile (solid) and NFW profiles with $c_{\text{vir}} = 5$ (short-dashed) and 10 (long-dashed). For reference, $c_{\text{vir}} \approx 3.3$ for $10^9 M_{\odot}$ at $z = 4$ in the Dutton & Macciò (2014) model using our cosmology. The horizontal, dotted line marks $r_{\text{LLS}} = r_{\text{vir}}$ and indicates that gas outside halos begins to determine the mean free path sometime between redshifts 5 and 6.

correct in detail, they are sufficient to gain physical intuition into the problem. The result in equation 12 is analogous to that in equation 11; both give the correspondence between density and ionization rate.² Since, at fixed Γ , gas self-shields at fixed physical density, the associated overdensity falls with increasing redshift. Finally, combining equation 12 with the density distribution in equation 8, the radius at which $\Delta(r_{\text{LLS}}) = \Delta_i$ is given by $r_{\text{LLS}} = x_{\text{LLS}} r_{\text{vir}}$, where

$$x_{\text{LLS}} = \frac{1}{3c_{\text{vir}}} \left(\tilde{D} + \frac{1}{\tilde{D}} - 2 \right),$$

$$\tilde{D} = \left[(3/2) (81 D^2 + 4 D)^{1/2} + 4 D + 1 \right]^{1/3}, \quad (13)$$

where $D \equiv (c_{\text{vir}}^3 / [3 A(c_{\text{vir}})]) (\Delta_{\text{vir}} / \Delta_i)$. The corresponding value for an isothermal profile is

$$x_{\text{LLS}}^{\text{isothermal}} = \left(\frac{\Delta_{\text{vir}}}{3 \Delta_i} \right)^{1/2}. \quad (14)$$

Figure 1 compares r_{LLS} as a function of redshift for different choices of the density profile. At low redshifts,

² Indeed, the two agree to within a factor of 2.

where Δ_i is large, sufficiently neutral gas resides only in the inner regions of the halos where $r < r_a$. Here, the resulting values of r_{LLS} are very similar among different profile choices. However, at larger redshifts, the value of Δ_i becomes only quasi-linear, and r_{LLS} exceeds the virial radius. At this point, outside the virial radius, r_{LLS} depends more strongly on the assumed shape of the density profile. The transition between the two regimes occurs sometime between redshifts 5 and 6 and is more rapid if we assume the observations of $\Gamma(z)$ as given (thick curves in the figure) because the decreasing ionization rate after $z \sim 5$ contributes to additional growth in r_{LLS} .

Below $z \sim 5$, we can safely use a halo-based absorber model to determine the probability distribution function (PDF) of overdensities $\Delta > \Delta_i$ by calculating the fractional volume occupied by each overdensity around a halo and integrating over the halo mass function, dn/dM , which we take to be Sheth-Tormen mass function (Sheth & Tormen 1999; Sheth et al. 2001), from $M_{\text{min}}^{\text{abs}}$ to infinity. $M_{\text{min}}^{\text{abs}}$ is the minimum halo mass capable of hosting absorbing gas and is given roughly by the filtering mass (Gnedin 2000; Noh & McQuinn 2014). Below $M_{\text{min}}^{\text{abs}}$, halos cannot retain their gas and infall of new gas is suppressed. The parameter effectively controls the number of absorbers by determining which halos they populate. For a chosen value of $M_{\text{min}}^{\text{abs}}$, the PDF of overdensity is

$$\frac{dP_V(\Delta_0, z)}{d \log \Delta} = \int_{M_{\text{min}}^{\text{abs}}}^{\infty} 4 \ln 10 \pi r_0^3 (1+z)^3 \left[\frac{d \ln \Delta}{d \ln r} \right]_{r_0}^{-1} \frac{dn}{dM} dM, \quad (15)$$

where r_0 is the radius at which the overdensity of a halo is Δ_0 ; $d \ln \Delta / d \ln r$ is evaluated at r_0 ; and r_0 , $d \ln \Delta / d \ln r$, and dn/dM are each functions of M and z .

In Figure 2, we assume, for the purpose of illustration, a fixed value of $M_{\text{min}}^{\text{abs}} = 10^{9.3} M_{\odot}$ and compare our model results for the gas around halos at $z = 2.5$, 4.5, and 6.0 to predictions for more diffuse intergalactic gas from the numerical simulations of Bolton & Becker (2009).³ At the two lower redshifts, Δ_i is in the regime where we can trust our model, while by $z = 6$, a significant amount of gas with $\Delta > \Delta_i$ lies outside the virial radius and the numerical treatment is more appropriate.⁴

Through our absorber model, we can also directly obtain the column density distribution of neutral gas

³ Note that we should not expect a perfect match of our results onto those of Bolton & Becker (2009) at Δ_{vir} for several reasons, including assumptions in their simulations that affect $M_{\text{min}}^{\text{abs}}$ and its evolution and small differences in our assumed sets of cosmological parameters (in particular, Ω_b and σ_8).

⁴ Note also that our density PDF is unlikely to be accurate for $\Delta \gtrsim 300$, when the effects of gas cooling, star formation and feedback become particularly important. In the redshift range of interest, Δ_i generally lies below this.

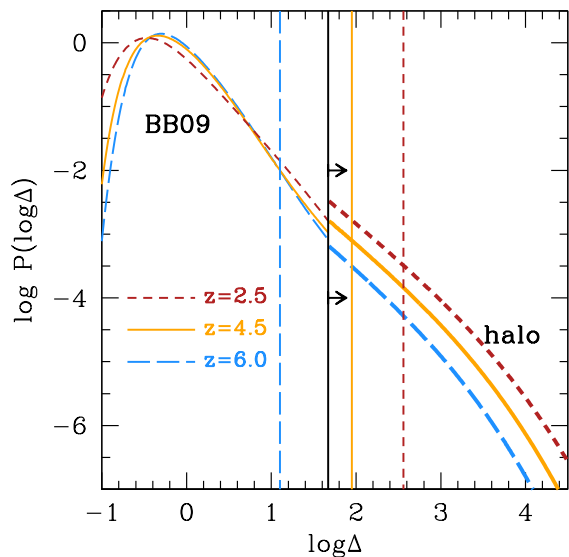


Figure 2. The PDF of overdensity, where $P(\log \Delta) \equiv dP_V/d\log \Delta$. Thin and thick curves show results from the numerical simulations of Bolton & Becker (2009) and from equation 15, respectively, at redshifts $z = 2.5$ (short-dashed), 4.5 (solid), and 6.0 (long-dashed). Vertical (colored) lines denote the overdensity corresponding to LLS with $N_{\text{HI}} = 10^{17} \text{ cm}^{-2}$ from equation 12. The vertical line (black) with arrows indicates the LLS overdensity for which that overdensity lies at the virial radius (see text); at lower redshifts (higher values of the LLS overdensity), absorbing gas lies entirely within halos described by our density PDF.

by computing the fractional projected area around each halo occupied by lines of sight with a given column density. Integrating over dn/dM yields

$$\frac{d^2 f(N_{\text{HI},0}, z)}{dN_{\text{HI}} dz} = \int_{M_{\text{min}}^{\text{abs}}}^{\infty} \frac{2\pi c}{H_0} \frac{b_0^2(N_{\text{HI},0})}{N_{\text{HI},0}} \left[\frac{d \ln N_{\text{HI}}}{d \ln b} \right]_{b_0}^{-1} \frac{dn}{dM} dM, \quad (16)$$

where the impact parameter b_0 corresponding to $N_{\text{HI},0}$ is given by (see also Murakami & Ikeuchi 1990)

$$N_{\text{HI},0} = 2b_0 \int_1^{\infty} n_{\text{HI}}(b_0 y, M, z) \frac{y dy}{(y^2 - 1)^{1/2}} \quad (17)$$

and we evaluate $d \ln N_{\text{HI}}/d \ln b$ at b_0 . Note that b_0 , $d \ln N_{\text{HI}}/d \ln b$, and dn/dM are each functions of both M and z .

In Figure 3, we compare the resulting distribution of column densities at $z = 4$ for different values of $M_{\text{min}}^{\text{abs}}$ the compilation of observations in Prochaska et al. (2010).⁵ At this redshift, we find good agreement from $N_{\text{HI}} \sim 10^{16.5} - 10^{20} \text{ cm}^2$ for $M_{\text{min}}^{\text{abs}} = 10^9 M_{\odot}$ consistent with the minimum mass required for sources as determined from observations of the UV galaxy luminosity

⁵ The results in Fig. 3 assume the emitter model in §3.2 and have been iterated for convergence in Γ and fit to the ionizing background observations of Becker & Bolton (2013).

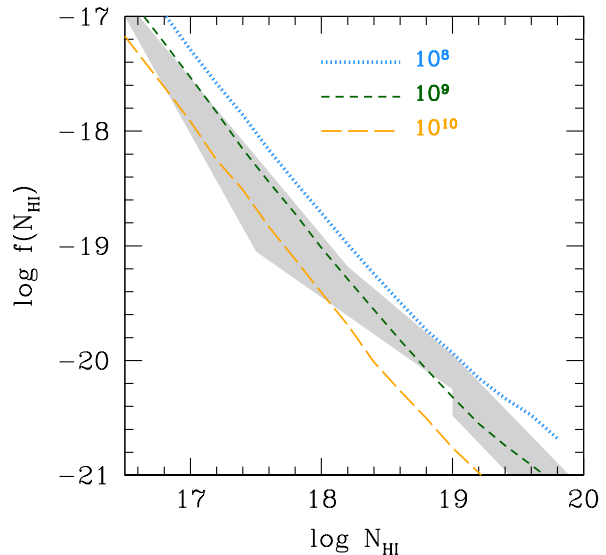


Figure 3. The column density distribution function at $z = 4$. Dotted (blue), short-dashed (green), and long-dashed (orange) curves show the computation from equation 16 for $\log M_{\text{min}}^{\text{abs}}/M_{\odot} = 8, 9,$ and 10 , respectively, using the source model in §3.2 with $\log M_{\text{min}}^{\text{abs}}/M_{\odot} = \log M_{\text{min}}^{\text{emit}}/M_{\odot}$ and values of f_{esc} best fit to the Becker & Bolton (2013) background ionization rate measurements. The shaded region denotes the observational compilation in Prochaska et al. (2010) and is well-described by our model with $\log M_{\text{min}}^{\text{abs}}/M_{\odot} = 9$ at this redshift (see text).

function (Muñoz & Loeb 2011) and inferred from numerical simulations (e.g., Noh & McQuinn 2014, and references therein). The distribution is also similar to the models published in Rahmati et al. (2013), where the self-shielding prescription produces only a modest deviation from a power-law over this range of column densities (see also Sobacchi & Mesinger 2014). The steep slope ensures that most of the opacity arises at the Lyman limit and that λ_{mfp} is primarily sensitive to the total abundance of absorbers, which is effectively set by $M_{\text{min}}^{\text{abs}}$, rather than the details of their column density distribution. Thus, while the effects of self-shielding may be starker at still higher column densities, we stress that these differences have little effect on the mean free path.

The column density distribution directly yields the mean free path of the IGM, which we can evaluate at the Lyman limit:

$$\lambda_{\text{mfp}}(z) = \frac{dl}{dz} \left[\frac{d\tau_{\text{eff}}(\nu_{912}, z)}{dz} \right]^{-1}, \quad (18)$$

where

$$\frac{d\tau_{\text{eff}}(\nu, z)}{dz} = \int_0^{\infty} dN_{\text{HI}} \frac{d^2 N}{dN_{\text{HI}} dz} \left[1 - e^{-N_{\text{HI}} \sigma_{\text{HI}}(\nu)} \right], \quad (19)$$

$dl/dz = cH^{-1}(z)(1+z)^{-1}$ is the proper distance per redshift interval for an evolving Hub-

ble parameter $H(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$, and where $\sigma_{\text{HI}}(\nu) = \sigma_{912}(\nu/\nu_{912})^{-3}$ is the ionization cross-section of neutral hydrogen with a value of $\sigma_{912} \approx 6.3 \times 10^{-18} \text{ cm}^2$ at $\nu_{912} = 3.29 \times 10^{15} \text{ s}^{-1}$, the frequency corresponding to the Lyman limit. Because of the exponential term in equation 19, column densities greater than $\sim 1/\sigma_{912} \approx 1.6 \times 10^{17} \text{ cm}^{-2}$ —that is, approximately the value corresponding to LLSs—will dominate the integral. However, note that we do include the contribution from optically thin absorbers at lower column densities.

3.2 Emitter Model

3.2.1 Galaxies

We adopt a simple model for the evolving ionizing emissivity of the universe resulting from star formation in galaxies. We compute the star formation rate within a dark matter halo as a function of its mass and redshift in a way specifically designed to reproduce observations of the UV luminosity function of Lyman-break galaxies and its evolution (Muñoz 2012):⁶

$$\dot{M}_\star = \frac{M_{\text{acc}}}{1 + \eta_w}, \quad (20)$$

where (McBride et al. 2009)

$$M_{\text{acc}} \approx 3 M_\odot/\text{yr} \left(\frac{M_{\text{halo}}}{10^{10} M_\odot} \right)^{1.127} \left(\frac{1+z}{7} \right)^{2.5} \quad (21)$$

at high redshift and $\eta_w \approx (400 \text{ km/s})/\sigma$. The halo velocity dispersion, σ , is a function of halo mass and redshift (Barkana & Loeb 2001):

$$\sigma = 46 \text{ km/s} \left(\frac{M_{\text{halo}}}{10^{10} M_\odot} \right)^{1/3} \left(\frac{1+z}{7} \right)^{1/2} \times \left[\frac{\Omega_m h^2 / \Omega_m(z)}{0.137} \frac{\Delta_c}{18 \pi^2} \right]^{1/6}. \quad (22)$$

For a 10^{10} (10^{12}) M_\odot halo at $z = 3$, $\sigma \approx 35$ (160) km/s, $1 + \eta_w \approx 13$ (3.5), and the average star formation rate is about 0.06 (40) M_\odot/yr .

To obtain the ionizing emissivity resulting from this galaxy model, we first compute the comoving star formation rate density of the universe by integrating equation 20 over the halo mass function,

$$\bar{\rho}_{\text{SFR}}(z) = \int_{M_{\text{min}}^{\text{emit}}}^{\infty} \dot{M}_\star(M, z) \frac{dn}{dM}(M, z) dM. \quad (23)$$

We plot the results in Figure 4 as a function of redshift for different values of $M_{\text{min}}^{\text{emit}}$ to demonstrate the changing evolution of $\bar{\rho}_{\text{SFR}}$ with minimum mass; as $M_{\text{min}}^{\text{emit}}$ increases, it moves into the tail of the mass function, and the abundance changes more rapidly. The figure further shows the consistency between our

⁶ For convenience, we ignore the scatter in star formation rate at fixed halo mass, which predominantly affects only the brightest end of the luminosity function.

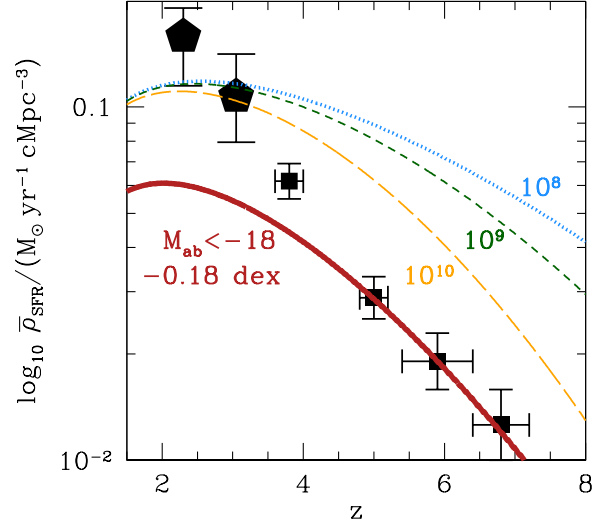


Figure 4. The evolving star formation rate density of the universe. Dotted (blue), short-dashed (green), and long-dashed (orange) curves show results from our emitter model (equation 23) for $\log M_{\text{min}}^{\text{emit}}/M_\odot = 8, 9,$ and 10 , respectively. Pentagons show observational results from Reddy & Steidel (2009) with an applied correction for dust and undetected sources. Squares denote measurements by Bouwens et al. (2007) and Bouwens et al. (2012) only for galaxies brighter than a rest-frame UV absolute magnitude of -18 with no dust correction. For comparison, the thick, solid (red) curve shows our model adopting the same limiting magnitude and removing a dust correction of 0.18 dex (see text).

model and observationally-based measurements from Reddy & Steidel (2009) at $z \sim 2-3$ that include corrections for both dust extinction and faint sources below the detection limit. At higher redshift, the Bouwens et al. (2007) and Bouwens et al. (2012) data reflect only detected galaxies and do not include a contribution from fainter objects, which could dominate the star formation rate density (e.g., Wyithe & Loeb 2006; Hopkins & Beacom 2006; Muñoz & Loeb 2011). Therefore, we expect these points to be only lower limits to the star formation rate density at high redshift. For comparison, we also show the results from our model if we remove a dust correction to the luminosity of 0.18 dex, consistent with the determination by Bouwens et al. (2007) at $z = 6$. The agreement between this result and the observed points at high redshift is not coincidental; recall that our model is based on a fitting to the observed luminosity function. Correcting for undetected sources flattens the comoving evolution of the source population but is neither sufficient to explain the flat evolution in Γ given the extreme sensitivity between Γ and ϵ derived by McQuinn et al. (2011) nor does it solve the issue of fine-tuning.

From the star formation rate density, we obtain the

comoving Lyman-limit emissivity,

$$\epsilon_{912}^{\text{gal}}(z) = f_{\text{esc}} l_{\text{ion}} \bar{\rho}_{\text{SFR}}(z), \quad (24)$$

by assuming values of the ionizing luminosity at 912 Å, l_{ion} , produced per star formation rate and of the ionizing escape fraction, f_{esc} , that are independent of both mass and redshift.⁷ While the former depends on the properties of the stellar population, the latter is still more uncertain with theoretical predictions generally conflicted about its dependence on mass and redshift (see Ferrara & Loeb 2013, and references therein). Because our model depends only on the product of the two quantities, we will, in practice, set $l_{\text{ion}} = 2.7 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1} M_{\odot}^{-1} \text{ yr}$ and leave f_{esc} as a free parameter. We then specify the source spectrum such that $\epsilon_{\nu}(z) = \epsilon_{912}(z) (\nu/\nu_{912})^{-\alpha_{912}}$ and assume $\alpha_{912} = 2.0$ to be consistent with the method in Becker & Bolton (2013, see the discussion in §5.1 of their paper). While in principle α_{912} and $f_{\text{esc}} l_{\text{ion}}$ may vary with redshift and/or halo mass, we assume constant values here to demonstrate that such variation over the redshift range from $z \sim 2\text{--}5$ is unnecessary to produce the flat evolution in the background ionization rate, in contrast with studies that invoke redshift-dependent escape fractions (e.g., Haardt & Madau 2012; Kuhlen & Faucher-Giguère 2012; Ferrara & Loeb 2013). Of course, f_{esc} may additionally vary at still higher redshifts to facilitate cosmic reionization.

3.2.2 AGN

In addition to galaxies, AGN may be important sources of ionizing radiation at the redshifts of interest. Haardt & Madau (2012) adopt the evolving quasar emissivity from Hopkins et al. (2007) who integrate the observed luminosity function down to -27 magnitudes in the rest-frame B-band assume a conversion factor from the B-band to the Lyman-limit based on composite spectra that is independent of luminosity and redshift. The resulting comoving emissivity is given by

$$\epsilon_{912}^{\text{AGN}}(z) = \frac{(10^{24.6} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}) (1+z)^{4.68} e^{-0.28z}}{e^{1.77z} + 26.3}. \quad (25)$$

While this calculation has, perhaps, fewer uncertainties than does the determination of the galaxy emissivity, this level of contribution from AGN is somewhat higher than that observed directly by Cowie et al. (2009). Because of this, Becker & Bolton (2013) argue that AGN make a negligible contribution to the emissivity. Given the uncertainties in whether, when, and by how much quasars contribute to ϵ_{912} , we adopt a flexible model in which the total emissivity is

$$\epsilon_{912}(z) = \epsilon_{912}^{\text{gal}}(z) + f_{\text{AGN}} \epsilon_{912}^{\text{AGN}}(z), \quad (26)$$

⁷ Note that this definition of f_{esc} is slightly different than what is measured in the literature.

with $\epsilon_{912}^{\text{gal}}$ and $\epsilon_{912}^{\text{AGN}}$ given by equations 24 and 25, respectively. Setting $f_{\text{AGN}} = 1$ is equivalent to adopting the AGN emissivity from Haardt & Madau (2012), while $f_{\text{AGN}} = 0.25$ approximately reproduces the observed AGN emissivity from Cowie et al. (2009, see Fig. 5).

3.3 Summary

We construct a model for absorbers (§3.1) in which the gas dominating the ionizing mean free path of the IGM is associated with dark matter halos above a minimum mass $M_{\text{min}}^{\text{abs}}$ and traces an NFW density profile with concentration given by Dutton & Macciò (2014). Halos above a minimum mass $M_{\text{min}}^{\text{emit}}$ also host galaxies, which we assume to be sources of ionizing radiation (§3.2), specifying the star formation rate as a function of halo mass and redshift to reproduce observations of the galaxy UV luminosity function and setting constant values for both the ionizing luminosity produced per star formation rate, l_{ion} , and the ionizing escape fraction, f_{esc} . We then include an additional component to the emissivity to approximate the contribution from AGN, which we assume to be a factor f_{AGN} times the Haardt & Madau (2012) level. The combined absorber+source semi-analytic model, thus, has four free parameters: $M_{\text{min}}^{\text{abs}}$, $M_{\text{min}}^{\text{emit}}$, the product $f_{\text{esc}} l_{\text{ion}}$, and f_{AGN} .⁸ However, in practice, we only allow f_{esc} to vary and fix the remaining parameters to well-motivated values (see Table 1). In particular, we typically set $M_{\text{min}}^{\text{abs}} = M_{\text{min}}^{\text{emit}}$ to highlight the relationship between sources and absorbers (while further reducing the number of free parameters), but note that the flat evolution that we find in $\Gamma(z)$ does not depend on a precise equivalence between these two minimum masses (see §5.1).

4 RESULTS

Combining our absorber and source models, we compute the ionizing background as

$$\Gamma(z_0) = 4\pi \int_{\nu_{912}}^{\infty} \frac{d\nu_0}{h_{\text{p}} \nu_0} J_{\nu_0}(z_0) \sigma_{\text{HI}}(\nu_0), \quad (27)$$

where h_{p} is the Planck constant,

$$J_{\nu_0}(z_0) = \frac{1}{4\pi} \int_{z_0}^{\infty} dz \frac{dl}{dz} \left(\frac{1+z_0}{1+z} \right)^3 \epsilon_{\nu}(z) e^{-\tau_{\text{eff}}(\nu, z, z_0)}, \quad (28)$$

$\nu = \nu_0(1+z)/(1+z_0)$, and

$$\tau_{\text{eff}}(\nu, z, z_0) = \int_{z_0}^z dz' \frac{d\tau_{\text{eff}}(\nu, z')}{dz'} \quad (29)$$

⁸ In principle, we could also vary α_{912} , the spectral slope of the emitters. However, within reasonable limits this has very little impact on our results.

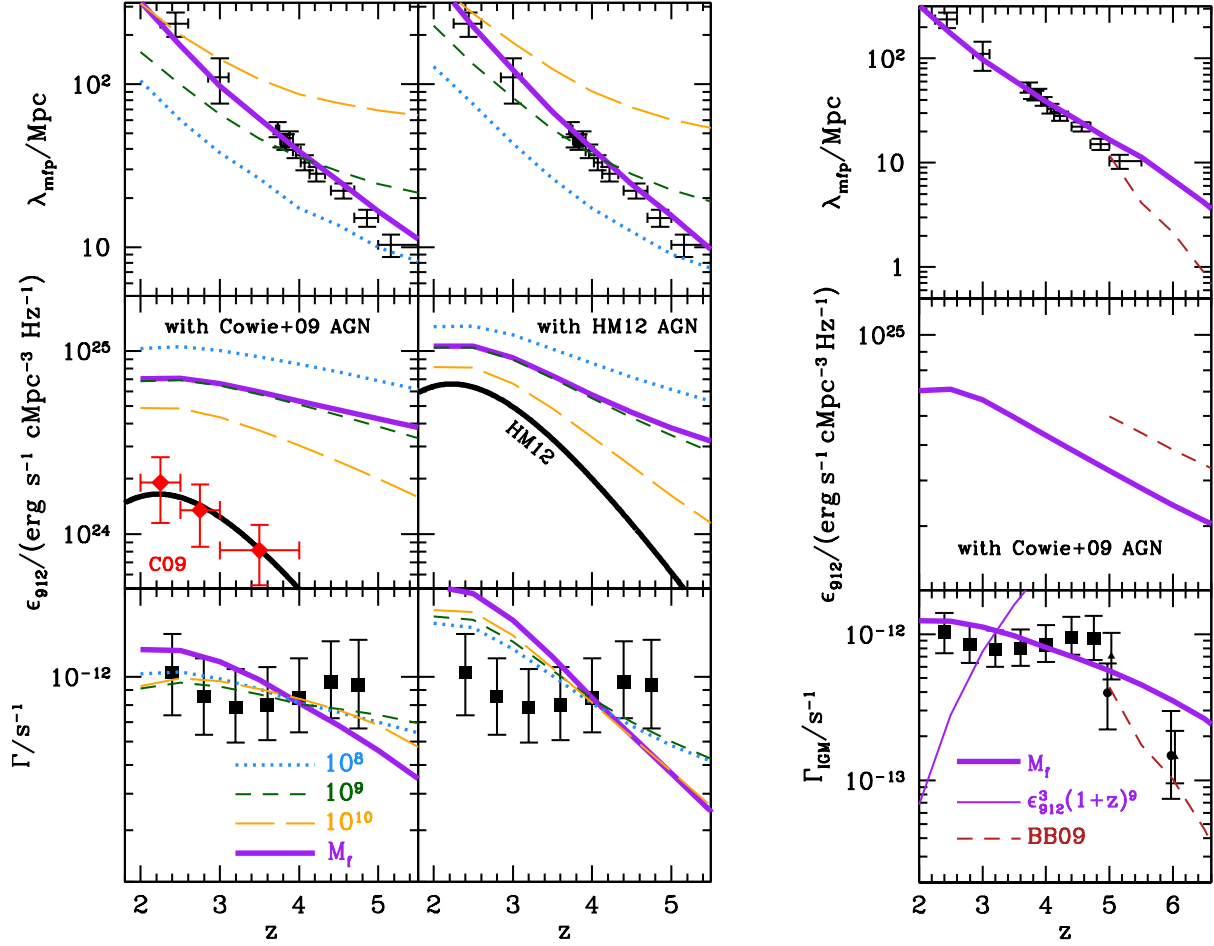


Figure 5. The redshift evolution of the mean free path of the IGM (top), the ionizing emissivity (middle), both evaluated at the Lyman limit, and the background ionization rate (bottom). Dotted (blue), short-dashed (green), long-dashed (orange), and solid (purple) curves show the model results best-fit to the Becker & Bolton (2013) measurements of Γ (square points) for $\log M_{\min}^{\text{abs}}/M_{\odot} = \log M_{\min}^{\text{emit}}/M_{\odot} = 8, 9, 10$, and M_f (equation 32), respectively (see Table 1). Mean-free-path measurements are taken from the compilation in Worseck et al. (2014). In the left column, we assume $f_{\text{AGN}} = 0.25$, consistent with observations from Cowie et al. (2009, diamonds, C09), while in the center column, we set $f_{\text{AGN}} = 1$ to add the contribution to the emissivity from AGN estimated in Haardt & Madau (2012, HM12), which is additionally denoted by the labeled thick (black) curve. In the right column, the thick, solid (purple) curve is the same as that from the left column, while the thin, solid (purple) curve shows the proper emissivity raised to the third power and arbitrarily normalized. The dashed (red) line shows the calculation using the Bolton & Becker (2009) density PDF (see text) with $\log M_{\min}^{\text{abs}}/M_{\odot} = \log M_{\min}^{\text{emit}}/M_{\odot} = M_f$. For comparison at $z = 5$ and 6, we have also included the measurements of Γ from Wyithe & Bolton (2011, adjusted by Becker & Bolton 2013, circles) and Calverley et al. (2011, triangles), artificially separated slightly in redshift for clarity.

with $d\tau_{\text{eff}}/dz$ given by equation 19. Equation 27 includes the redshifting effects of cosmological expansion, important at $z \lesssim 3$ when the mean free path is comparable to the proper size of the universe. At higher redshifts, the background ionization rate is simply proportional to the product of the emissivity and the mean free path as in equation 1. However, Γ itself is also an input into the mean free path where it controls the ionization fraction x_{HI} and, consequently, the column density distribution.

Therefore, to obtain final values of λ_{mfp} and Γ , we begin with a starting value of $\Gamma = 10^{-12} \text{ s}^{-1}$ at all redshifts and iterate equation 27 until convergence.

We primarily compare our results to the measurements from Becker & Bolton (2013) from $z = 2.4$ –4.75. These authors computed $\Gamma(z)$ by comparing calibrations from numerical simulations with observed IGM optical depths from stacked samples of Sloan Digital Sky Survey quasar absorption spectra (Becker et al. 2013).

Their determinations are summarized in Tables 1 and 2 of Becker & Bolton (2013). Because the resulting values of Γ at different redshifts are correlated, in appendix A, we combine their published covariance matrix of statistical errors with their estimated Jeans smoothing and systematic uncertainties to produce a total covariance matrix with which to judge the goodness of fit between our model and the observations. Note that we make the conservative choice not to correlate systematic uncertainties at different redshifts. Thus, the true uncertainties may still be somewhat larger.

We can also compare our results for the mean free path to those inferred from recent observations of quasar absorption lines. Note that the measured mean free path in the literature is not identical to that given in equation 18. Instead, the appropriate value for comparison is (see Becker & Bolton 2013, for a discussion)

$$\lambda_{\text{mfp}}^{\text{obs}}(z_2) = \int_{z_1}^{z_2} dz \frac{dl}{dz}, \quad (30)$$

where z_2 is the measurement redshift and

$$\int_{z_1}^{z_2} dz' \frac{d\tau_{\text{eff}}[\nu_{912}(1+z')/(1+z_2), z']}{dz'} = 1. \quad (31)$$

We compare our results to data from O’Meara et al. (2013) at $z = 2.44$, Fumagalli et al. (2013) at 3.00, Prochaska et al. (2009) at $z = 3.73$ –4.22, and Worseck et al. (2014) at $z = 4.56$ –5.16 as compiled by Worseck et al. (2014).⁹

Figure 5 shows the results of our model. The top and middle panels show the mean free path from our absorber model and the ionizing emissivity from our emitter model, respectively, while the bottom panel shows the computed background ionization rate. We summarize our model results and χ^2 values in Table 1, where, for each set of model parameters, the mass- and redshift-independent value of f_{esc} is fit to the Becker & Bolton (2013) data only.

4.1 The Flatness of Γ from $z \approx 2$ –4

For each choice of $M_{\text{min}}^{\text{abs}}$ and $M_{\text{min}}^{\text{emit}}$, we set $l_{\text{ion}} = 2.7 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1} M_{\odot}^{-1} \text{ yr}$ and fit a mass- and redshift-independent value of f_{esc} to the Becker & Bolton (2013) data for Γ from $z = 2.4$ –4.75 (see §A). We present the results for each model in Table 1 and Figure 5. The class of models for non-evolving $M_{\text{min}}^{\text{abs}} = M_{\text{min}}^{\text{emit}}$ reproduce the data extremely well for any $\log M_{\text{min}}^{\text{abs}}/M_{\odot} = 8$ –10 if AGN do not strongly contribute to the emissivity (i.e., $f_{\text{AGN}} = 0.25$). However, if AGN do contribute at the level assumed by Haardt & Madau (2012), then our model only consistent with the data for $\log M_{\text{min}}^{\text{abs}}/M_{\odot} \lesssim 9$.

However, in general, models with constant minimum mass produce somewhat shallower evolution in

Table 1. Results

$M_{\text{min}}^{\text{abs}}/M_{\odot}$	$M_{\text{min}}^{\text{emit}}/M_{\odot}$	f_{AGN}	f_{esc} (%)	χ^2
10^8	10^8	0.25	2.8	3.5
10^9	10^9	0.25	1.7	2.3
10^{10}	10^{10}	0.25	1.1	3.1
M_f	M_f	0.25	1.8	9.1
10^8	10^8	1	2.3	13.4
10^9	10^9	1	1.3	15.3
10^{10}	10^{10}	1	0.6	22.1
M_f	M_f	1	1.4	29.6
10^8	10^9	0.25	3.0	4.8
10^8	10^{10}	0.25	3.4	9.1
10^8	10^{11}	0.25	5.0	26.8

the mean free path than observed. Lower values of $M_{\text{min}}^{\text{abs}} = M_{\text{min}}^{\text{emit}}$ under-predict λ_{mfp} at lower redshifts, while higher values over-predict λ_{mfp} at higher redshifts. Of course, the minimum mass is expected not to be constant but to evolve with redshift owing to a combination of the ionizing background, the Jeans instability, and heating and cooling (e.g., Gnedin 2000; Barkana & Loeb 2001; Hoeft et al. 2006; Okamoto et al. 2008; Naoz et al. 2009; Noh & McQuinn 2014). Qualitatively, as the universe grows less dense at lower redshifts, larger halo masses are required to retain gas. This effect would steepen our mean free path evolution and push our results toward with the measurements by producing a lower minimum mass at $z = 5$ than at $z = 2$.

Here, we test such a model in which $M_{\text{min}}^{\text{abs}}$ and $M_{\text{min}}^{\text{emit}}$ evolve with redshift. We adopt the simple prescription of setting the minimum masses for both galaxies and absorbers equal to the filtering mass (Gnedin 2000, using the updated definition of Naoz et al. 2009):

$$M_f = 2.2 \times 10^{10} M_{\odot} \left(\frac{1+z}{5} \right)^{-3/2} f(z, z_{\text{rei}})^{3/2},$$

$$f(z, z_{\text{rei}}) = 0.3 \left[1 + 4 \left(\frac{1+z}{1+z_{\text{rei}}} \right)^{2.5} - 5 \left(\frac{1+z}{1+z_{\text{rei}}} \right)^2 \right], \quad (32)$$

where we assume a reionization redshift of $z_{\text{rei}} = 9$. This prescription effectively evaluates the Jeans criterion at the mean density of the universe without accounting for the detailed formation histories of halos (Noh & McQuinn 2014). Nevertheless, it serves as a standard test case. We again fit f_{esc} (still presumed to be independent of mass and redshift) to the Becker & Bolton (2013) data. The results are listed in Table 1 and plotted in Figure 5. For $f_{\text{AGN}} = 0.25$, we find $f_{\text{esc}} = 0.018$. This simple model still maintains the flat evolution in Γ while simultaneously predicting $\lambda_{\text{mfp}}(z)$ consistent with observations. Therefore, we will refer to this as our fiducial model, ascribing the remaining deviations to the approximate nature of equation 32

⁹ We ignore the slight difference in cosmological parameters between this paper and observational works in the literature, which typically take $\Omega_{\text{m}} = 0.3$ rather than 0.28.

and leaving a more detailed fitting of all available data to future work.

4.2 The Drop-off in Γ at $z \gtrsim 5$

Our model breaks down at $z \gtrsim 5$ when gas outside halos begins to dominate the absorption. This is clearly seen in Figure 1, where gas with column densities of 10^{17} cm^2 moves outside the virial radius, and a decreasing $\Gamma(z)$ makes the transition rapid. Furthermore, Figure 2 shows that, by $z = 6$, this gas has low overdensity, which is more appropriately modeled by the Bolton & Becker (2009) simulation of the IGM than by our profiles of halo gas. In this regime, the PDF remains almost constant with redshift while the source population continues to evolve, and we recover the scenario investigated by McQuinn et al. (2011). As a result, we expect the evolution of ϵ_{912} to produce a large drop in Γ toward higher redshifts, and indeed, this is what the data show. Wytke & Bolton (2011) and Calverley et al. (2011) both measure the background ionization rate at $z = 6$ and find values nearly an order of magnitude lower than do Becker & Bolton (2013) at $z = 4.75$. However, new measurements suggest that the ionization rate at $z \gtrsim 5$ may also be significantly patchier than at lower redshifts (e.g., Becker et al. 2014).

To quantitatively compare the evolution of the ionizing background at $z \gtrsim 5$ to the data, we first translate the PDF of intergalactic gas from Bolton & Becker (2009) into a column density distribution and then compute the mean free path via equation 18. Since the NFW profile we assumed for halo gas is likely not appropriate for clouds in the IGM, we simply use the association between N_{HI} and Δ in equation 12. Then, from Furlanetto & Oh (2005), the column density distribution corresponding to a density PDF is

$$\frac{d^2 f(N_{\text{HI}}, z)}{dN_{\text{HI}} dz} = \frac{\Delta}{N_{\text{HI}}} \frac{d\Delta}{dN_{\text{HI}}} \frac{dP_V(\Delta, z)}{d\Delta} \frac{c}{H_0} \bar{n}_{b,0} (1 - Y_{\text{He}}) x_{\text{HI}}, \quad (33)$$

where $\bar{n}_{b,0}$ is the mean baryon number density of the universe today and x_{HI} is set by recombination balance including our prescription for self-shielding. Since equation 12 is based on an assumption of Jeans length-sized absorbers in the optically thin limit and to compensate for the inexact matching between the Bolton & Becker (2009) PDF and ours, we renormalize the resulting mean free path to approximately match onto the value predicted by our fiducial M_f model (with $f_{\text{AGN}} = 0.25$) at $z = 5$. Once again, because Γ is an input into equation 33 through x_{HI} , we must iterate the computation of equation 27.

The free parameters in this case are $M_{\text{min}}^{\text{emit}}$, f_{AGN} , and $f_{\text{esc}} l_{\text{ion}}$. Setting $M_{\text{min}}^{\text{emit}} = M_f$, $f_{\text{AGN}} = 0.25$, and $l_{\text{ion}} = 2.7 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1} M_{\odot}^{-1} \text{ yr}$, we fix $f_{\text{esc}} = 0.026$ so that $\Gamma(z = 5)$ approximately matches the value produced by our fiducial model. Figure 5 compares our results to the data at $z \geq 5$ from Wytke & Bolton (2011, as slightly adjusted by

Becker & Bolton 2013) and Calverley et al. (2011). We find that the transition to the absorbing gas outside of halos does reproduce a precipitous drop in the evolution in Γ from $z \sim 5-6$. Note that since we only adjust parameters to obtain $\Gamma(z = 5)$, this is a genuine outcome of the model. Furthermore, this simple calculation predicts a break in the evolution of the mean free path from its power-law behavior at $z \lesssim 5$ (Worseck et al. 2014) toward a steeper decline at $z \gtrsim 5$, despite no sharp change in the emissivity.

5 SENSITIVITY TO MODEL ASSUMPTIONS

5.1 The $M_{\text{min}}^{\text{abs}}-M_{\text{min}}^{\text{emit}}$ Equivalence

The flat evolution of the background ionization rate from $z \sim 2-5$ rests on the association between sources and absorbers through the formation of cosmic structure, and in our model, we have largely set $M_{\text{min}}^{\text{abs}} = M_{\text{min}}^{\text{emit}}$ to reflect this. However, these two minimum masses need not be precisely equal to maintain the connection between sources and absorbers and produce a constant ionizing background. Physically, this scenario may result from the suppression of star formation due to low metallicity and corresponding low molecular fractions in galaxies that are otherwise able to retain their gas (e.g., Krumholz & Dekel 2012). As a test of this effect on Γ , we fix $\log M_{\text{min}}^{\text{abs}}/M_{\odot} = 8$ and consider progressively larger values of $M_{\text{min}}^{\text{emit}}$, each of which is also held constant in time. The results are summarized in Table 1 and plotted in Figure 6. The fit to the Becker & Bolton (2013) measurements only becomes intolerable if $\log M_{\text{min}}^{\text{emit}}/M_{\odot} \gtrsim 10$. This is because both absorption and emission are completely dominated by halos near the minimum mass only if the minimum mass is above the knee of the mass function, i.e., the non-linear mass M_{NL} .¹⁰ If, instead, both minimum masses are below this non-linear mass, then there will be an contribution to both absorption and emission from halos near M_{NL} that will keep the two processes linked regardless of the specific values of $M_{\text{min}}^{\text{abs}}$ and $M_{\text{min}}^{\text{emit}}$. Thus, since $M_{\text{NL}}(z = 2) \approx 5 \times 10^{11} M_{\odot}$ and $M_{\text{NL}}(z = 5) \approx 10^9 M_{\odot}$, our results are insensitive to the precise equivalence between the minimum masses for sources and absorbers.

5.2 The Shape of the Density Profile and the Self-Shielding Prescription

In our model, the distribution of neutral hydrogen around galaxies as a function of host halo mass and redshift is a combination of our assumed NFW density profile for gas in halos as well as our ionization prescription with its implementation of gas self-shielding.

¹⁰ The non-linear mass is the smoothing mass for which the variance of density fluctuations in the universe is approximately unity (see, e.g., Barkana & Loeb 2001).

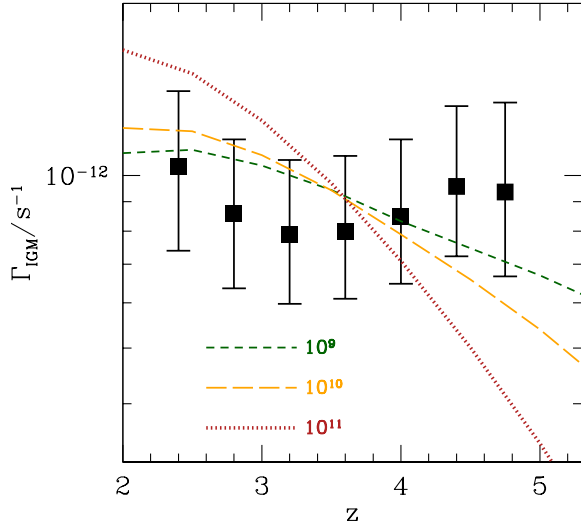


Figure 6. The evolution of the ionization rate for $M_{\min}^{\text{abs}} < M_{\min}^{\text{emit}}$. $\log M_{\min}^{\text{abs}}/M_{\odot} = 8$ in all cases. We show results for $\log M_{\min}^{\text{emit}}/M_{\odot} = 9$ (short-dashed, green), 10 (long-dashed, orange), and 11 (dotted, red). The points are the measurements from Becker & Bolton (2013), and the χ^2 values when compared to this data are listed in Table 1.

However, there can be strong fluctuations in the shape of the dark matter profile about the analytic average in equation 8 (e.g., Diemer & Kravtsov 2014), and the distribution of gas relative to the dark matter is complicated by accretion mode, cooling, and feedback (e.g., Faucher-Giguere et al. 2014). Moreover, equations 10 and 11, which encapsulate our self-shielding prescription, represent only approximate fits of a complicated radiative-transfer process.

Yet, the flatness in $\Gamma(z)$ is insensitive to all of these details. This is because, in our model, the dominant contributions to the evolution of the mean free path are the expansion of the universe, the evolution in the minimum mass, and the addition of new halos through the growth of structure rather than a change in the absorber cross-section. Heuristically, if absorbers are of order the Jeans length (Schaye 2001), then the lack of evolution in the physical density for self-shielding (equation 11) implies that the size of absorbers is also roughly redshift independent. To see this in detail, consider the evolution of $r_{\text{LLS}}/r_{\text{vir}}$ in Figure 1. $r_{\text{LLS}}/r_{\text{vir}}$ increases by just over a factor of 2 from $z = 2$ –4.5, while the virial radius, which is approximately proportional to $M_{\text{halo}}^{1/3} (1+z)^{-1}$ (Barkana & Loeb 2001), decreases by nearly the same factor. As a result, at a fixed halo mass, r_{LLS} evolves very little, and the evolution in the mean free path is linked to the growth of structure and the changing abundance of sources. Therefore, the details that effectively control r_{LLS} do not strongly influence our result.

One could imagine implementing a very different model for the profile of density or ionization state

around halos that does produce significant evolution in r_{LLS} . However, such a model would still have to account for the inevitable cosmological effects on the absorber population. Since our current framework is already consistent with observations of $\lambda_{\text{mfp}}(z)$, a model that additionally includes a rapidly evolving r_{LLS} would likely break this agreement.

6 CONCLUSIONS

We have shown that a framework in which both neutral absorbing gas and the sources of ionizing radiation are associated with the same population of dark matter halos and linked to the growth of cosmic structure generically produces a flat evolution in the background ionization rate from $z \sim 2$ –5 as measured from quasar absorption lines (Becker & Bolton 2013). Analytically, Γ is approximately proportional to $(\epsilon/n_a)^3$ rather than to ϵ^3 so that, for fixed f_{esc} , an increase in the emissivity (in the comoving frame) is compensated for by an increase in the abundance of absorbers, and indeed, the result of a non-evolving Γ is largely independent of our detailed assumptions about the minimum halo mass that supports absorbers and sources, the shape of the density profile around halos, and the self-shielding of neutral gas. Moreover, adopting a minimum halo mass for absorbers and emitters which evolves in a way consistent with theoretical expectations, our model also reproduces measurements of $\lambda_{\text{mfp}}(z)$. However, the relationship between sources and absorbers breaks down at still higher redshifts when the mean density of the universe is large enough that gas outside halos must contribute significantly to the absorption of ionizing radiation. At this point, the background ionization rate becomes extremely sensitive to the source emissivity, as suggested by McQuinn et al. (2011), and Γ drops precipitously at $z \sim 5$ –6, consistent with observations (Wyithe & Bolton 2011; Calverley et al. 2011). Thus, our model presents a generic solution to the puzzling flatness and sudden evolution of the ionizing background that does not require a specific evolution of the ionizing escape fraction.

The basic association between sources and absorbers in our model can be tested observationally by cross-correlating LLSs in quasar spectra and catalogs of faint galaxies or between LLSs and damped Lyman- α absorbers (e.g., Font-Ribera et al. 2012). However, in detail, such tests will depend on assumptions about the gas profile of dark matter halos. We leave a more in depth study of different possible halo profiles and configurations and the resulting observable signatures to future work.

In addition to explaining the flat evolution of the background ionization rate, our model reveals new insights into both the production and absorption of ionizing photons that presage future progress. First, to fit our model to observations of $\Gamma(z)$, we generically require f_{esc} of order a couple percent, roughly

consistent with direct measurements (Nestor et al. 2013; Jones et al. 2013; Mostardi et al. 2013), and suggest that radiation-hydrodynamics simulations (e.g., Pawlik & Schaye 2011; Finlator et al. 2012) could provide even sharper constraints. Moreover, the connection between LLSs and halos in our model implies that metal lines observed in quasar absorption spectra and associated with HI column densities $\gtrsim 10^{17} \text{ cm}^{-2}$ at $z \lesssim 5$ probe the circumgalactic medium within halos rather than intergalactic gas. However, our results suggest that these same metal lines at even higher redshifts are more likely to be true tracers of the IGM (see, e.g., Simcoe et al. 2012; Finlator et al. 2013). Finally, our model provides cosmological context for the evolution of the mean free path, which we attribute to inevitable cosmological processes—a combination of (a) the expansion of the universe, (b) the evolution of the minimum halo mass below which accretion is suppressed, and (c) the changing abundance of halos—without requiring the changes in absorber size, mass, or ionization fraction suggested by Worseck et al. (2014).

An association between sources and absorbers of ionizing radiation is quickly becoming part of the general picture of the IGM. If true, this idea will allow future studies of the background ionization rate and quasar absorption lines to studies, not just the star formation in galaxies, but their gas and halo structure as well.

7 ACKNOWLEDGEMENTS

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APPENDIX A: FITTING OBSERVATIONS OF THE BACKGROUND IONIZATION RATE

To compute the symmetric covariance matrix, \vec{C} , given in Table 1, we start with the covariance matrix for the statistical uncertainties in $\log \Gamma$ given by Table 2 of Becker & Bolton (2013) and add the Jeans smoothing uncertainties and the systematic uncertainties quoted

Table 1. Covariance Matrix (x100)

z	2.4	2.8	3.2	3.6	4.0	4.4	4.75
2.4	1.070	0.145	0.114	0.094	0.083	0.077	0.076
2.8		1.013	0.101	0.079	0.074	0.071	0.069
3.2			0.939	0.089	0.069	0.070	0.075
3.6				0.898	0.092	0.065	0.074
4.0					0.879	0.117	0.079
4.4						0.911	0.183
4.75							1.182

by these authors to all elements and to diagonal elements, respectively. We then determine our best-fit models by minimizing

$$\chi^2 = (\vec{x}_{\text{mod}} - \vec{x}_{\text{obs}})^T \vec{C}^{-1} (\vec{x}_{\text{mod}} - \vec{x}_{\text{obs}}), \quad (\text{A1})$$

where \vec{x}_{obs} and \vec{x}_{mod} are vectors containing means values of $\log \Gamma$, respectively, computed by our model and measured by Becker & Bolton (2013) for the same set of redshifts.